A 17 GHz HIGH GRADIENT LINAC HAVING STAINLESS STEEL SURFACES IN THE HIGH INTENSITY MAGNETIC AND ELECTRIC FIELD REGIONS OF THE STRUCTURE*

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Abstract

To avoid surface erosion damage and to assist in understanding RF breakdown limitations imposed on high gradient linac operation, a gradient hardened structure is being fabricated having high temperature brazed and machined stainless steel surfaces located in the high E-field region of the beam apertures and in the high H-field regions of the racetrack shaped coupling cavities. The microwave design parameters and physical dimensions of this 17GHz, $2\pi/3$ mode, 22-cavity structure were established specifically to allow comparison of its high gradient performance to that of a similar all-copper structure tested under identical conditions, using an existing 4X power amplifying, RF recirculating dual ring system. Use of the 6X thicker skin depth material, the resulting de-Q-ing effects and the minimal reduction of beam energy (2%) associated with the strategically located lossy surfaces are discussed; fabrication techniques are described; and design parameters of the gradient hardened linac and the 17GHz power amplifying system are presented.

INTRODUCTION

The results of high power experiments with full length linear accelerator structures [1,2,3] using RF pulse widths in the range of 100 to 400 ns have indicated that the maximum accelerating gradient is essentially independent of the operating frequency. Moreover, an extensive 11.4GHz test program at SLAC using copper structures has established the accelerating gradient upper limit for acceptable long term operation to be approximately 65MV/m. Attempts to operate disc loaded TW structures at higher gradients, to satisfy the >100 MV/m requirement for future linear colliders, have resulted in RF breakdown at the disc irises and coupling cavity apertures; and in some instances, permanent phase changes have occurred due to erosion of the copper surfaces.

To assist in understanding the limitations imposed on high gradient operation, and to minimize surface damage, a gradient hardened 17GHz TW linac structure is being fabricated using high temperature brazed, non-magnetic stainless steel inserts in the high H-field regions of the dual feed, racetrack shaped input coupler cavity at the lips of the side wall coupling apertures, and in the high E-field region of the disc irises, as indicated in Figure 1. This work is based on a previously described technique [1] that made use of the superior high temperature strength properties of stainless steel (refer Table 1) to solve an electric field surface erosion problem encountered after long service with a prototype high power TW output structure in a 17GHz relativistic klystron.

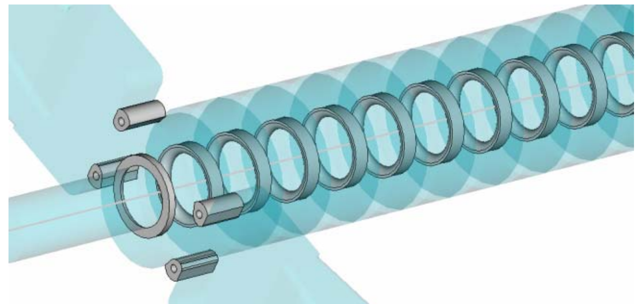

Figure 1: Location of brazed stainless steel inserts.

Table 1: Parameter Comparison of Materials

Parameter	OFHC Copper	Type 304 Stainless Steel
Tensile Strength (psi)	28000*	79000
Yield Strength (psi)	2000	35000
Modulus of Elasticity (psi)	16×10^6	29×10^6
Maximum Elongation (%)	60	54
Melting Temp. (°C)	1083	1454 – 1499

* At room temperature

4X POWER AMPLIFIER IMPLICATIONS

The microwave parameters and physical dimensions of the gradient hardened linac test structure were designed to match the feedback loop insertion loss and the mechanical interface requirements of the high peak power dual ring RF recirculating system shown schematically in Figure 2. In this system, two 6dB hybrids are attached directly to the linac test structure to form two parallel feedback loops so that, on the initial pass, 25% of the source RF power

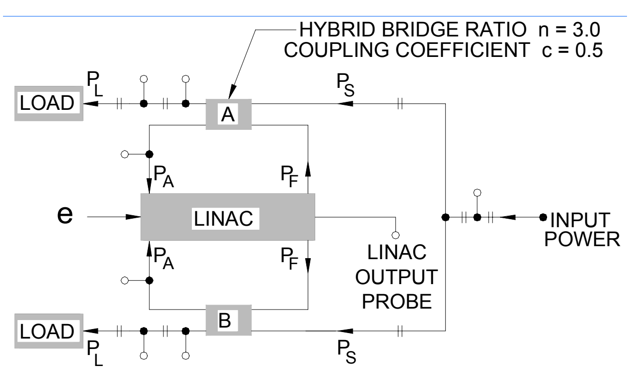

Figure 2: 4X Power amplifier dual recirculating rings with an embedded 17GHz linac test structure.

*Work performed under the auspices of the U.S. Department of Energy SBIR Grant No. DE-FG02-05ER84362.

enters the linac, and 75% is transmitted to the loads. For a loop loss of 1.25dB (including beam loading), 75% of the linac input power will be returned to the bridge; and with a correctly phased feedback loop, 75% of this returned power will be added to the linac input power, and 25% (in counter phase) will cause a load power reduction. After 20 successive loop recirculations, the load arm power will be reduced to zero, and the linac input power will build up to a level 4 times greater than the source power, as indicated in Figure 3. After full buildup is attained, a constant power level will be maintained until the source pulse is terminated. Thus, a loop transit time of 11ns is required to achieve an RF flattop of 150ns with a source pulse width of 370ns.

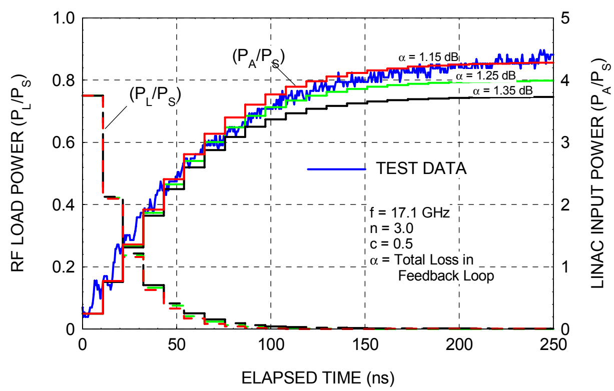

Figure 3: 4X Power buildup and load power decay during successive recirculations.

To ensure that the loop loss and transit time parameters of the power amplifier would be conserved when operating with the gradient hardened linac structure, the de-Q-ing effects of using different configuration stainless steel inserts were studied; and means of compensating for these effects were investigated.

STAINLESS STEEL INSERTS

The gradient hardened structure was designed to duplicate the phase orbit characteristics of the 22-cell, all-copper linac structure presently integrated into the 4X power amplifier. This structure, shown in Figure 4, incorporates cavities with phase velocities slightly larger than c to provide correct asymptotic bunch location for high gradient operation with a 550kV injector.

Although 304 stainless steel has a surface resistivity ≈6 times greater than annealed high purity copper, it was possible to avoid undesirable degradation of the cavity Q by limiting the brazed inserts to only that small fraction of the cavity surface exposed to high surface fields. The iris contour of the stainless steel insert in each 1.45mm thick copper disc was formed by using 0.68mm radii smoothly blended from the sides of the disc to a 0.09mm flat in the bore, with extension along the disc sides to a region where the surface E-field is reduced to 65-70% of the maximum value. Simulation results indicated that, for the range of cavity parameters considered (a/λ=0.14 to 0.18, and phase velocities from c to 1.015c), the use of 304L stainless steel brazed inserts in the disc irises would result in a Q

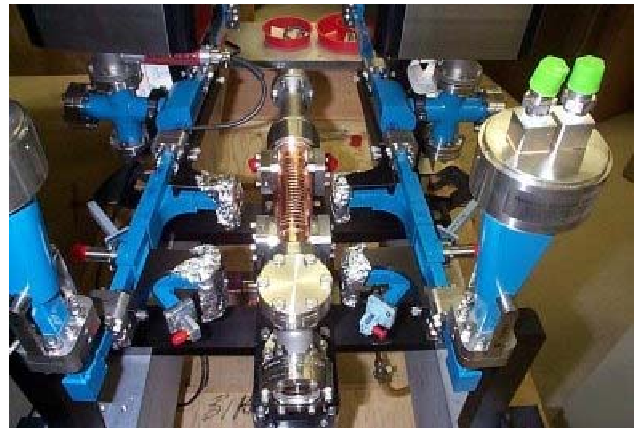

Figure 4: 17GHz linac all-copper structure in the 4X peak power amplifier system.

reduction of 16%. It can be noted that, even with a linac attenuation parameter as high as τ = 0.3Np (more than twice the value required for this application), a 16% increase in the surface loss of a near-uniform impedance structure will result in only a 2% reduction of beam energy because the product of the unit length increased attenuation and reduced shunt impedance remains essentially constant, and the beam energy is proportional to $(1-e^{-\tau})/\tau$.

To compensate for the de-Q-ing effect of the stainless steel so that the required loop loss is maintained, the disc iris diameter of the gradient hardened structure was made 5.4% larger than the all-copper structure, and the system design parameters were finalized, as listed in Table 2.

The dual feed, racetrack-shaped input coupler configuration simulated in Figure 5, shows the location of the stainless steel inserts (and associated copper heat sink holes) that form the lips of the coupling apertures. The magnetic field values shown at the surface of the cavity wall and coupling aperture are normalized to the peak of the modified Bessel function (100), and indicate that, with a compact single cell coupler assembly, the use of thick asymmetrically radiused lips can limit the magnetic field enhancement to a moderate value (2.2:1).

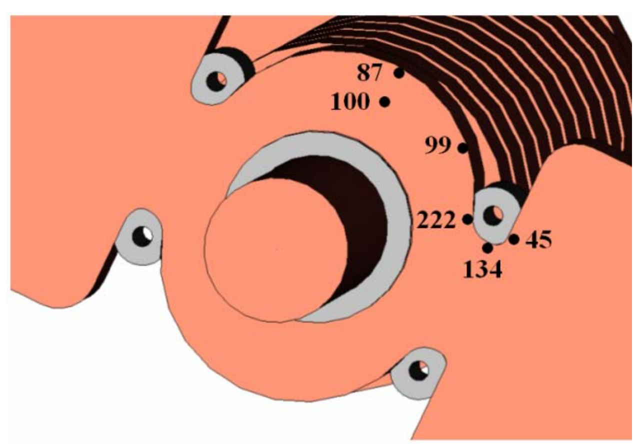

Figure 5: Racetrack cavity configuration showing the normalized values of the magnetic field, the copper heat sink holes, and the stainless steel brazed inserts forming the asymmetrically radiused lips of the coupling apertures.

Table 2: Design Parameters of the Gradient Hardened 17GHz Linac Structure and the Power Amplifier

Frequency		17136	MHz
Operating Mode		$2\pi/3$	
Number of Cavities (including Racetrack Couplers)		22	
Cavity Phase Velocities		4 at c, 2 at 1.005c, 2 at 1.010c, and 14 at 1.015c	
Disc Thickness		1.45	mm
Stainless Steel Iris Diameter		6.00	mm
Number of Stainless Steel Irises		23	
Stainless Steel Skin Depth		3.1	μm
Copper Skin Depth		0.51	μm
Structure Attenuation Parameter (including stainless steel irises)		0.124	Np(+lips)
Linac Structure Harmonic Mean Group Velocity		0.044c	
Linac Structure Filling Time		9.7	ns
Output Phase/Frequency Sensitivity of Linac Structure		3.5	deg/MHz
Output Phase/Temperature Sensitivity of Linac Structure		1.0	deg/°C
Feedback Loop Transit Time		11.2	ns
Feedback Loop Total Loss		1.25	dB
Feedback Loop Total Phase		8280	deg
Feedback Loop Phase Dispersion		4.1	deg/MHz
Time to Attain 99.5% Steady State RF Power Buildup		210	ns
Input Power to Dual Ring	8	20	MW
Linac Input Power	32	80	MW
Average Accelerating Gradient	64	101	MV/m
Maximum Surface Gradient	150	236	MV/m

FABRICATION DETAILS

Brazing and machining investigations to ensure void-free bonding of the metal inserts resulted in the use of prefabricated mixed metal billets brazed at a higher temperature than the subsequent gold-copper alloy brazing of the final machined components. Figure 6 shows typical billet assemblies for body cavities and RF cut-off noses, and the embedded stainless steel buttons and cylinders that formed the final machined disc iris inserts. Also shown are racetrack coupler billets with

Figure 6: Mixed metal billets being prepared for nickel alloy brazing prior to preliminary and final machining.

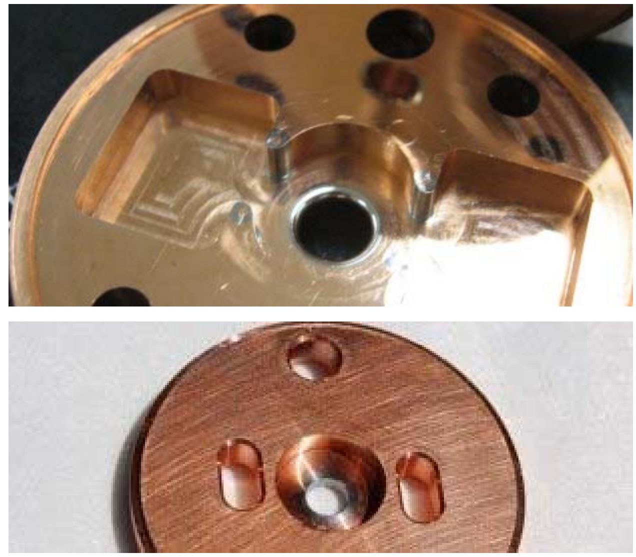

Figure 7: High temperature brazed stainless steel inserts and copper heat sinks shown in the racetrack input coupler, and a typical iris insert cavity, prior to final machining.

accurately pre-located holes for positioning the hollow stainless steel posts and copper heat sink pins that formed the asymmetrically radiused coupler lips in a subsequent milling operation, as shown in the upper photograph of Figure 7.

Accurately reproducible values of passband and resonant frequency, measured after repeated braze cycles using stainless steel iris cavity test assemblies, have confirmed the geometric stability of this configuration. Similar tests using high temperature brazed molybdenum iris inserts were also satisfactorily performed; these resulted in a slight increase in resonant frequency.

CONCLUSIONS

Despite the increase in surface resistivity of stainless steel compared to copper, because of the superior high temperature strength characteristics and the substantially greater skin depth, there are empirical and theoretical arguments suggesting that the use of stainless steel should enable high gradient operation at surface temperatures in excess of values associated with surface damage in copper cavities. High power 17GHz linac tests are planned to evaluate the validity of these arguments and to determine if they influence the threshold value for reliable high gradient operation.

REFERENCES

[1] Structure Breakdown Workshop, SLAC, Stanford, August 2000, http://www-project.slac.stanford.edu/lc/wkshp/RFBreakdwn/struct_breakdown_wkshp.htm.
[2] Workshop on High Gradient RF Cavities, Argonne National Lab., Oct. 1993, http://www.hep.anl.gov/rf/.
[3] US Workshop on High Gradient Research for Multi TeV Linear Colliders, SLAC, Stanford, July 2005, http://www.slac.stanford.edu/grp/ara/HGWorkshop/HGWorkshop.htm.

